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Brazilian case study for biogas energy: Production of electric power, heat and automotive energy in condominiums of agroenergy

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ABSTRACT

Brazilian projects on Condominiums of Agroenergy for Family Agriculture have demonstrated the feasibility of combining preservation of the environment to productivity and income generation through technologies accessible to small farmers gathered in a condominium energy. Such projects have also demonstrated the feasibility of transmuting the environmental liabilities of the Brazilian agricultural sector into electricity and fertilizer, working with the voluntary commitment to decrease the emission of greenhouse gases in Brazil by 2020. In this sense, this study presents examples as the Combined Heat and Power Generation Plant (CHP) fueled by biogas produced by Ajuricaba small farmers in the town of Marechal Rondon, Brazil. This work will provide an overview of the thermodynamical and chemical biogas energetic processes and also the technological components that constitute a CHP for the generation of thermal energy (grain dryer, use in household stoves and heating poultry houses), electricity (self-generation and sale of electricity to public company) and biogas future utilization in Brazilian farm vehicles.

Contents

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1. Introduction

In recent years important international agencies and institutions of the power sector have been evaluating how Brazil has highlighted the potential energy use of biogas obtained from the deposit of waste biomass [1–4]. It is the exploitation of a renewable energy resource and therefore is eligible to receive Certified Emission Reductions (CERs), which encourages the diversification of the energetic matrix and decentralized generation, besides the related obvious environmental benefit.

It fits in the classification of residual biomass the vegetable useless rests for consumption or planting, effluent solids and liquids from agribusiness in general or specifically from livestock or poultry that can be degraded as waste and manure [5,6]. In livestock, specifically, wastes have been dumped directly into the soil as fertilizer or have been disposed off in open-air lagoons, causing problems such as odor, water contamination and increased concentration of methane (CH_4) in the atmosphere, which can translate into dangerous contributions to the atmospheric greenhouse effect. It is well known that CH_4 has the potential to absorb infrared energy 24 times greater than that of carbon dioxide (CO_2) and the resulting greenhouse effect can lead to drastic climate changes in the next few decades [7,8].

The energy use of biogas comes basically from its mostly flammable component, methane. In order to mitigate the production of atmospheric methane, one can perform its energy recovery from the capture through the production of biogas. The main constituents of biogas are methane and carbon dioxide, with a composition of approximately 50–80% methane, with the remainder being primarily carbon dioxide. Other gases, such as hydrogen sulfide (H_2S), nitrogen (N_2), hydrogen (H_2) and carbon monoxide (CO), also compose biogas, but in lower concentrations [9–13]. Methane fermentation is a complex process, which can be divided into four phases of degradation: hydrolysis, acidogenesis, acetogenesis and methanation, according to the main process of decomposition in this phase. The individual phases are carried out by different groups of microorganisms, which partly stand in syntrophic interrelation and place different requirements on the environment [14]. In principle, methane formation follows an exponential equation dependent on time *t*. The most outstanding production of biogas is made by the process of anaerobic digestion of organic waste. The energy applications can be summed up to that applied to cases of obtaining thermal energy and use in electric vehicles. Fig. 1 illustrates the main features of the biogas energy route.

It is well known that, particularly for agricultural cases, the worldwide energy potential only with manure production is estimated at about 20 EJ (20×10^{18} J) [15]. The energy use of these wastes in Europe and Asia has created a benchmark in the industry standardizations, especially for the case of energy from biogas [16–18]. This success in recent years has also arrived in Brazil, as is the case in some urban projects such as the Basic Sanitation Company of the State of São Paulo (SABESP) that generates energy through biogas produced at Sewage Treatment Plant of Barueri [19]. Also in rural Brazil, the use of agroenergy from biogas is a reality that is growing at increasing rates. The main projects are located in southern Brazil [2,3,20,21].

Such advances in Brazilian bioenergy – in particular condo agroenergy biogas as an enabler of small rural properties – bring high strategic value to Brazil, creating a dimension, in the rural sector, of self-generation, which would result in the release of energy to meet other demands of society, not discarding the generation of surplus electricity, which can be commercialized in the national system. The potential of the Brazilian family agriculture for the production of energy should not be underestimated. In Brazil this sector covers about 13.8 million people, or 77% of the population employed in agriculture, according to the National Institute of Colonization and Agrarian Reform (INCRA) and the United Nations Food and Agriculture Organization (FAO) [22–26].

In this aspect, the experience of Agroenergy Condominium for Family Agriculture, developed since 2009 by the Itaipu Office of Renewable Energy in the Ajuricaba River watershed (Marechal Candido Rondon, Western Paraná, Brazil), has demonstrated the feasibility of combining the preservation of the environment to productivity and income generation through technologies

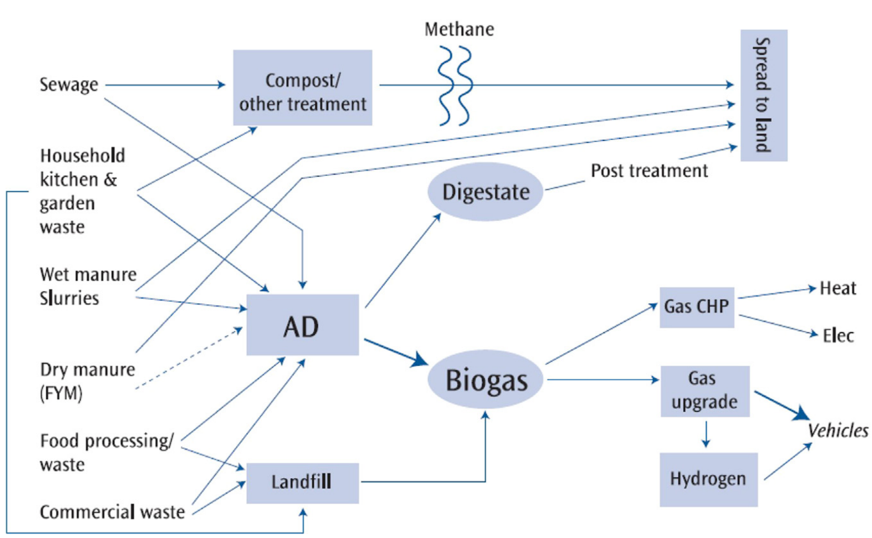

Fig. 1. Biogas energy route from anaerobic digestion (AD) for thermal utilization and electric vehicles. In this paper it will be used for the emphasis for power plants (CHPs) or direct automotive use. Adapted from [77].

accessible to small farmers gathered in a condominium energy [2,27]. A typical co-generation unit, like the one located at Condominium Ajuricaba, provides power from an electric moto-generator, driven by the internal combustion of biogas, and thermal energy through ovens that harness electricity generation and generation of direct heat by burning [28–35]. Moreover, the vehicular use of the energy of purified biogas from automotive pumps can be installed as well in such Condos.

The present article explores technological issues of the simultaneous generation of thermal and electrical energy in a micro-co-generation unit located in typical Brazilian agroenergy condominiums, from the use of biogas as a renewable fuel produced from waste by the process of anaerobic digestion. The feasibility of the proposed system or, briefly, the co-generation with biogas, can be seen not only by the production of low-cost energy and energy independence, but also by demonstrating the environmental viability in generation. The work is divided as follows: Section 2 contextualizes a first example of Condominium of Agroenergy, the Ajuricaba one, and its main physical and geographical aspects, introducing an overview on biogas energy production. In Section 3 the technological characteristics of biogas thermal energy in Ajuricaba will be explained. Section 4 discusses how biogas is used for self-generation, in the production of surplus electric power and in the development of new technologies such as the control panel to synchronize the electricity generated with that from the distribution network. The case of power generation in Colombari farm, Paraná, is presented. Section 5 discusses the prospects for implementation of a pilot system for use in condo vehicles. In Sections 6 and 7, after a general explanation about the advantages of biogas power and advantages in Ajuricaba site, some final concluding remarks will be presented.

2. Biogas in Agroenergy – example 1: Ajuricaba condominium, Paraná, Brazil

The project Agroenergy Condomium for Family Agriculture of Sanga Ajuricaba (Condomínio de Agroenergia de Agricultura Familiar, CAAF) was launched in August 2009 and it was developed in a partnership among Itaipu Hydroelectrical Dam, Institute of Technical Assistance and Rural Extension (Emater-PR), Companhia Paranaense de Energia (Copel), City Hall of Marechal Candido Rondon (PR), Embrapa, National Movement of Small Farmers (MPA), Institute of Applied Technology and Innovation (Itai), Itaipu Technological Park Foundation (PTI) and the International Center for Renewable Energies – Biogas. The main objective in such a facility is the achievement of concrete references for bioenergy in Brazilian family farming and also the development of specific criteria for its support in the economical, environmental, social and energetical aspects [2].

The partnership for such a project has demonstrated the feasibility of transmuting the environmental liabilities of the Brazilian agricultural sector into electricity and fertilizer, working with the voluntary commitment that the country has taken in the World Climate Conference in Copenhagen, to decrease the emission of greenhouse gases in Brazil by 36–39% by 2020. It is estimated that the use of Brazilian agriculture biogas inside the energetic matrix will contribute to reducing the emission of methane gas, which equates

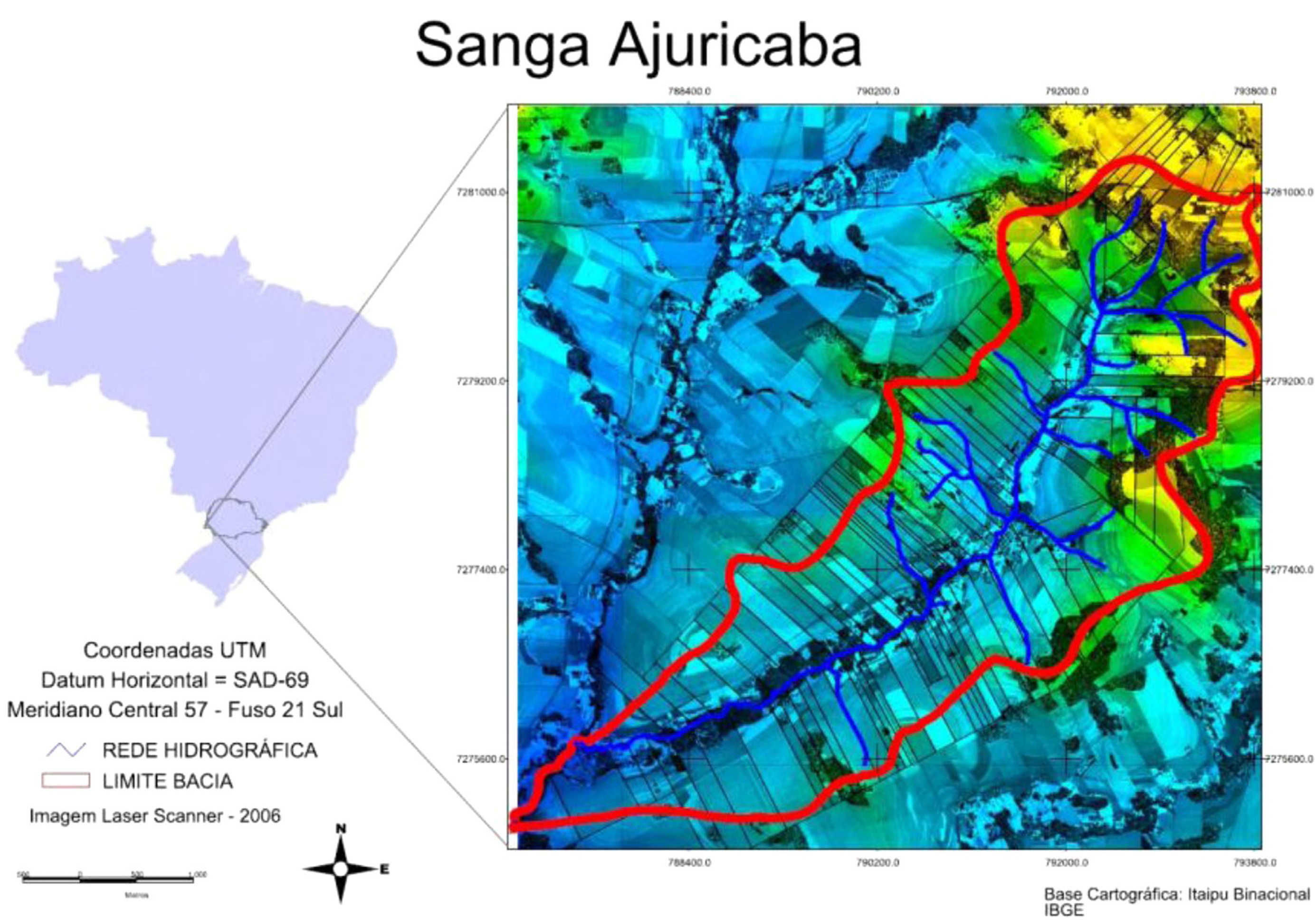

Fig. 2. Geographic location in Brazil of Ajuricaba Condominium in the town of Marechal Candido Rondon, Paraná.

to approximately 77.8 million ton of CO_2 annually. In this sense, the project Ajuricaba will introduce an emission reduction of approximately 1400 t of CO_2 per year when fully operational [2].

CAAF is located in the river basin Ajuricaba, within the municipality of Marechal Candido Rondon, Paraná State, Brazil (Fig. 2). The electricity generated will be used for inner power consumption purposes or sold to state-owned power distribution (Copel). Nowadays, biogas heat is used in grain drying, heating water for animals in the condo properties and even in the refrigeration of perishable products. The automotive application, which is in the research phase, might have directed its use for the supply of vehicles and agricultural machinery from filtering and appropriate adaptation of biogas.

The project consists of 33 family farms, totaling a herd of about 400 cows and 5000 hogs. Each of the properties has a digester, producing a total of 570 m^3/day of biogas, which is carried by 25.5 km of pipelines linked to the microthermoelectric (MCT). The pipeline is the product of a rural social technology incorporated from the biogas produced at family-scale farming. This technology, which produces biogas in small scales inside the system of condominium properties, is of fundamental importance to farmers, allowing them to enter the economical chain of biogas.

The recovery of electric power comes from a 100 kVA generator engine group connected to the net of distributed power. The structure installed in the MCT allows the installation of 4 generators, thereby creating the perspective to support research and development within a high methane concentration system.

Regarding the biogas conversion into thermal energy, in Ajuricaba MCT a grain dryer is installed, with total capacity for 470 sacks of grain. The produced biogas is used through direct or indirect heating, mainly to dry grains like corn, beans and soy. The system is dimensioned so that the producer himself dries the grain, without the need for hiring of manpower, and thus reducing the cost of drying by up to 90%.

To increase the concentration of CH_4, removing the H_2S from the product, a biogas treatment unit – BTU – is installed, which enables biogas filtering. This biogas, or after the filtering process, biomethane, is applied to the generator engine group for conversion into electricity. The high quality of biomethane allows vehicular application of biogas. In this sense, a proper technology is already being developed in a partnership between Itaipu and Petrobras researching centers.

Besides the explained biogas applications in MCT, producers can also use the biogas for cooking, heating water for bathing and heating water for cleaning milking equipment. These applications bring comfort to the families of farmers, besides reducing costs and increasing income.

3. Use of thermal energy in Agroenergy Condominiums

3.1. Generation of thermal energy from biogas

A considerable concentration of methane in biogas makes it a flammable gas, and the utilization of its calorific value is highly achievable. The burning of biogas can lead to the use of thermal energy directly and also to power generation (when the burning is applied in a thermal engine, e.g. Diesel or Otto engines, that operates in an electric generator). A flowchart summarizing this use is shown in Fig. 3. The burning of biogas therefore has a range of clear applications such as home or industrial heating, heating of swimming pools or ponds for breeding (aquaculture), heating stables, aviaries and pig livestock houses, application in the use of grain dryer, heating greenhouses, stoves and even in refrigeration systems [33].

In [88] it is reported that pure methane at standard temperature and pressure has a calorific value of about 33,980 kJ/m^3.

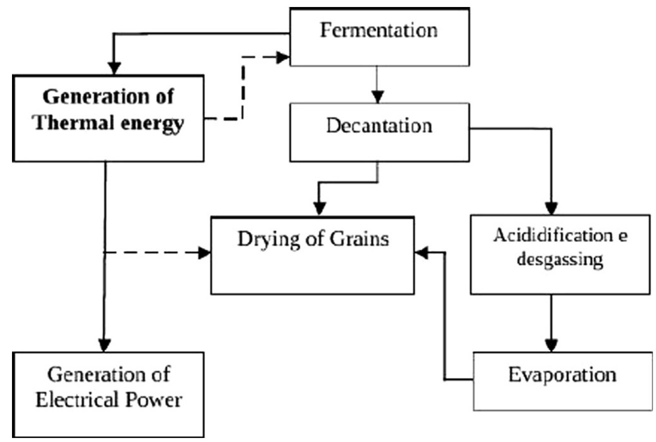

Fig. 3. Use of thermal energy (dotted lines). The biogas burning and the use of its calorific properties can help in the process of fermentation, accelerating it and, consequently, in the process of biogas decantation. The biogas burning can, e.g., be used in ovens that promote the drying of grains. Also, the generation of thermal energy, when it happens inside an engine chamber, can be transformed in physical work in an electrical engine, generating electrical power.

The biogas with 65% methane has a calorific value of about 22,353 kJ/m^3, because only methane will burn. When analyzing gaseous fuels, such as biogas, particularly those with low energy content due to dilution with various non-combustible gases, it is considered important to assess the flame speed during combustion, the flammability limit and flame temperature. Besides, 1 m^3 of biogas with 65% methane is equivalent to 0.6 m^3 of natural gas or 0.882 l of propane or 0.789 l of butane or 0.628 l of petrol or 0.575 l of fuel oil or 0.455 kg of bituminous coal or 1.602 kg of dry wood [33,88].

The flammability limit indicates the maximum and minimum percentages of the fuel mixture for combustion to occur. The limits of flammability of methane are between 5% and 15% by volume in the mixture with air. The theoretical flame temperature of methane in a stoichiometric air mixture, including the separation, is 1918 °C [33,88]. However, the theoretical flame temperature decreases when the concentration of non-combustible increases; therefore the flame temperature is a function of the content of water vapor and methane [90] and may go from 1871 °C (biogas with 60% methane) to 1816 °C (biogas with 40% methane) [88,89].

The use of biogas for heating and cooking has been in practice since a long time in countries like India, China and Nepal [36–40]. The use of biogas for cooking and heating begins with an efficient stove. Biogas stoves are relatively simple appliances which can be manufactured by local blacksmiths or metal workers. Stoves may be constructed from mild steel or clay. Clay burners are widely used in China and their performances have been satisfactory. All gas burners follow the same principle. The gas arrives with a certain speed at the stove, a speed created by the given pressure from the gas plant in the pipe of a certain diameter. The jet at the inlet of the burner increases this speed, thus producing a draft which sucks air (primary air) into the pipe. The primary air must be completely mixed with the biogas by widening the pipe to a minimum diameter. The 2-flame burners are the most popular type [41]. For a larger range of uses of biogas in stoves, see [42].

3.2. Grain dryer in the Condo Ajuricaba

The first example of application of thermal energy from biogas in Agroenergy Condos is a grain dryer that can generate parallel heat by burning biogas in an adapted furnace (thus eliminating the use of firewood). Fig. 4 shows the structure and basic equipment contained in the dryer. A more complete and detailed study of all the component parts is available in [43].

Grain drying is one of the steps of preprocessing of agricultural products and it aims to remove part of the water contained therein, characterized by a process of simultaneous transfer of heat and humidity between the product and the drying air, which is monitored by a control mechanism based on sensors that observe the inlet temperature, the mass contained in the dryer, the furnace and the environment. The ideal humidity for standard storage conditions in Brazil is 13%, being recommended to avoid drying below 14%, which would reduce the weight and performance of industrial grain mass [44]. Some of the main advantages of drying in agricultural production are as follows: crops can occur earlier providing the area for new plantings and seedings; minimizes product loss in the field; allows storage for longer periods, without the danger of product deterioration and maintains the power of germination for long periods; and prevents the growth of microorganisms and insects.

The main characteristics of the equipment illustrated in Fig. 4 can thus be summarized as follows. The furnace is made of solid brick masonry, endowed with grids formed by angle iron, with steel door and burner with 6 iron pipes, perforated and connected in parallel, with an independent input control of oxygen. The heat exchanger is of solid brick masonry, being located above the furnace chimney with galvanized steel. The diffuser is solid brick masonry, having apertures adapted to the semicircular shape of the tunnels by means of galvanized sheet. The fans (blowers), one for each set collector, with 5 HP engine power (using the electricity generated by the biogas) have a flow rate of 9500 m^3/h and a pressure of 70 mmH_2O, which connect the collectors or the heat exchanger to the drying chamber. The drying chamber is made of solid masonry brick in a circular shape with an internal diameter of 7.3 m, with drying bed slatted wooden coated with metal mesh, with a height of 0.9 m and a total volume of 37.7 m^3 (470 sacks). The dryer also features temperature measurement instruments (thermometers) and pressure control (pressure gauges) to allow monitoring and control of burning safely. The main equipment handling and storage parts are moenga, the elevator, conveyor and silo.

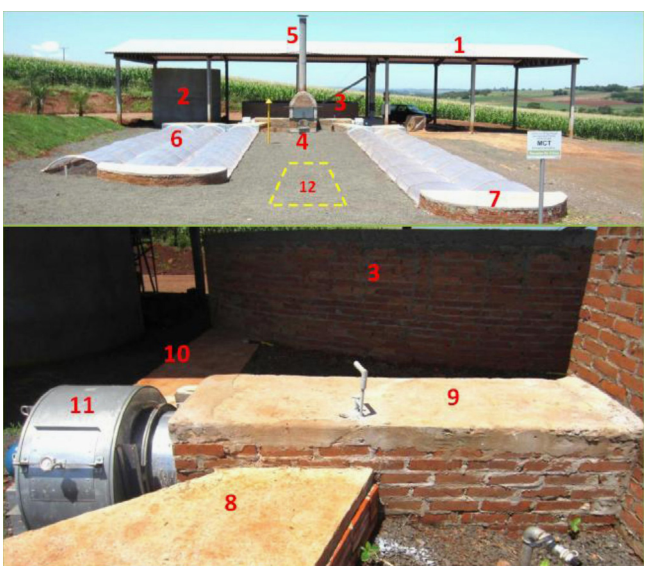

Fig. 4. Basic structure and equipment of the grain dryer in CAAF: (1) shed, (2) silo, (3) drying chamber, (4) furnace, (5) chimney, (6) solar collectors [not in the current design], (7) curved, (8) diffuser, (9) tunnel furnace, (10) tunnel to the dryer, (11) blower, (12) drain position.

To correctly approach the energy performance of the CAAF dryer, the variables of the energy analysis, as highlighted by [45], can be divided into input variables, system parameters and output variables. Among the input variables management moisture content is more accessible, making its ideal levels below 18% [44,45]. This provides a shorter drying time, higher integrity of grains, less amount spent on pest control, and reduction in power consumption and heat. System parameters such as capacity, engine power and airflow can affect the performance of the dryer, such as the opening of closed exchanger that can optimize the heating but also cause insufficient airflow. Among the output variables, the final moisture content is the parameter that defines the output of the product. The monitoring of the process is indispensable to avoid super-drying or to avoid the driving of wet grains, which leads to the growth of fungus and consequently in quality loss.

The air is heated indirectly in the heat exchanger by burning biogas into the furnace and sucked by the blower through the tunnels until the drying chamber. The blower motors have a total output flow of 19,000 m^3/h. The biogas supplied by CAAF in thermal mode usually has a concentration of approximately 60% methane. Fig. 5 shows the flowchart related to the heating process from burning biogas. Figs. 6–8 show the charts of monitoring the drying tests with three different values of volume of corn (102 sacks, 247 sacks and 470 sacks). These tests were made between January and February 2012 (see [43] for a full description).

A summary of three experiments can be carried out to observe the performance of the dryer in the CAAF MCT. To load 102 sacks, there was a preheat of 5 min with combustion of biogas with a concentration of 60% methane, under constant pressure, with half (1/2) log opening, which corresponds to a flow of 24.1 m^3/h. The temperature and humidity averages values were, respectively, 33 °C and 45%, and the sharp rise of the progressive humidity occurred from 20 h, reaching a maximum of 52% at 21 h. The average temperature of the dryer was 39.1 °C, with a maximum of 43.7 °C. The grain with initial moisture of 17.2% showed a drying rate of 0.7 pt/h. To load 247 sacks, preheat was applied until obtaining 400 °C at the furnace, burning biogas with a concentration of 65% methane. The temperature was maintained at an

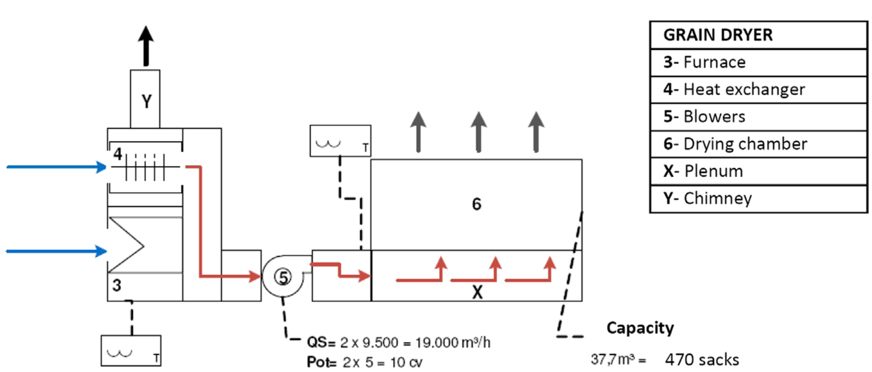

Fig. 5. Flowchart for heating air with the choice of heat source in the combustion of biogas.

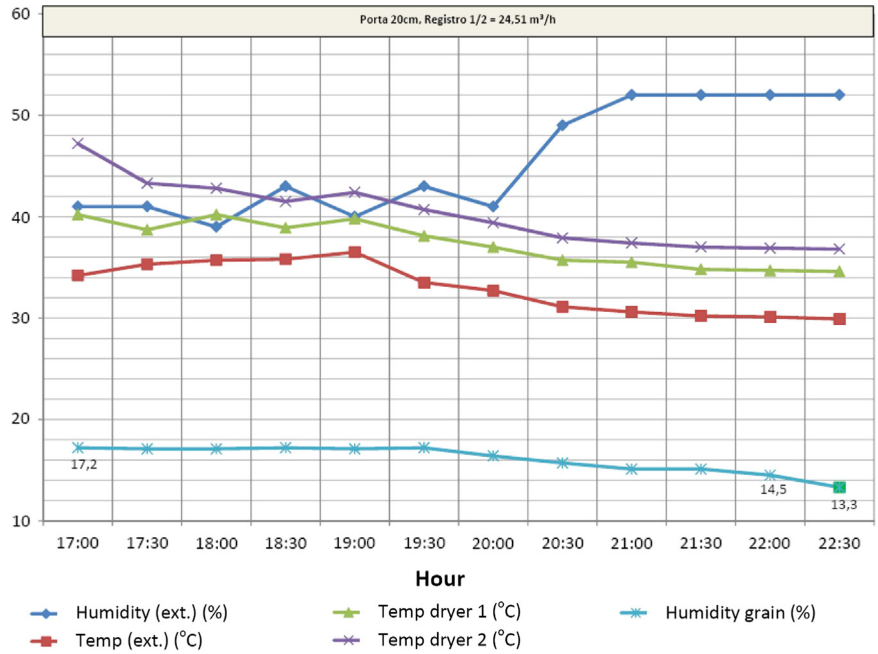

Fig. 6. Monitoring of drying for 102 sacks of corn (biogas with 60% methane).

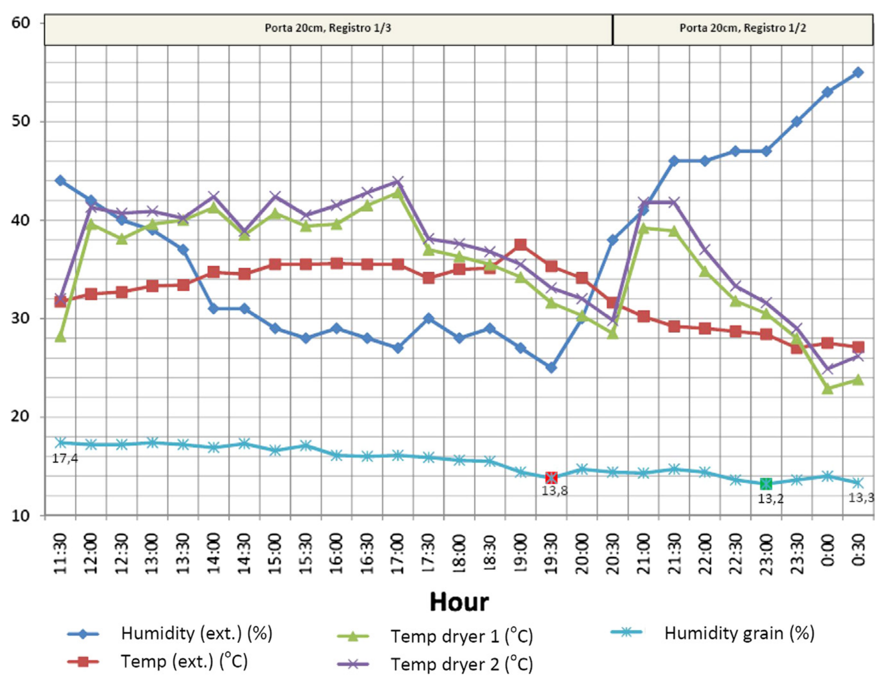

Fig. 7. Monitoring of drying for 247 sacks of corn (biogas with 65% methane).

average of 28.7 °C and humidity of 37%, with progressive increase in humidity up to 55% at 30 h. The average temperature of the dryer was 38.6 °C, with a maximum of 43.4 °C. The grain with 17.4% initial moisture presented a drying rate of 0.5 pt/h, reaching 10% moisture. To load 470 sacks, there was a preheat of 5 min with combustion of biogas with a concentration of 92% methane and opening 1/2 record corresponding to a flow rate of 24.1 m^3/h. The average temperature of the dryer was 44.6 °C, with a maximum of 49.6 °C. The moisture of the grain reached 13%.

Regarding the advantages and disadvantages of the CAAF dryer some considerations can be made based on the tests described above. Initially, using biogas with 60% methane and flow rate of approximately 12.44 m^3/h, the system heats, reaches a temperature of 45 °C, but cannot maintain it, with the primary interference in addition to humidity environment, oversizing of current engines. Using the 92% methane and flow of 24.51 m^3/h, the system warms up, the temperature exceeds 45 °C, and reduces interference from ambient humidity, but cannot maintain the reached temperatures.

Another issue is the energy efficiency of the dryer. It is the measure of the relationship between the energy expended to remove a water mass of the grain mass and grain mass itself in question. The total energy of the system considers the sum of the consumed energy and the energy from the consumption of biogas,

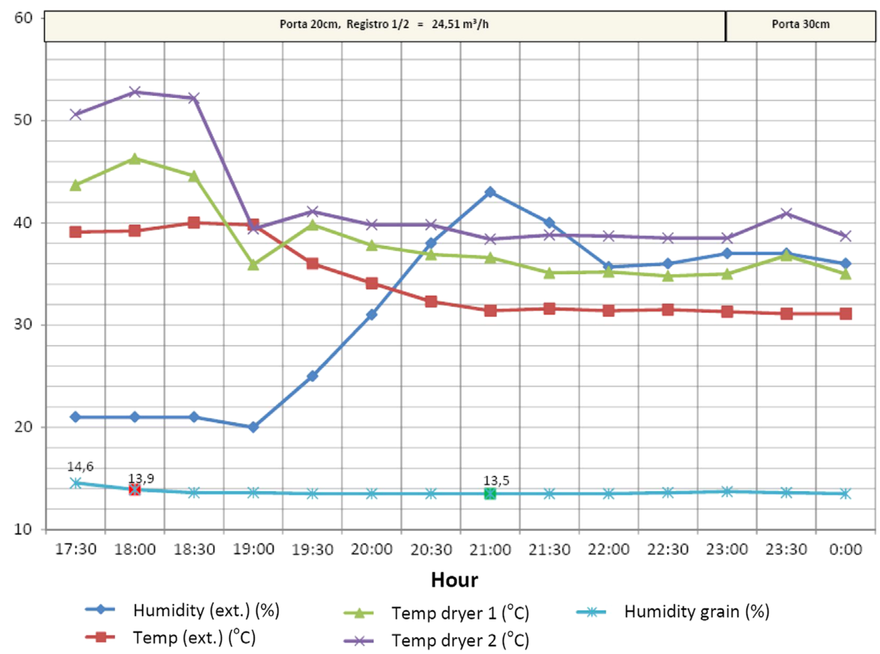

Fig. 8. Monitoring of drying for 470 sacks of corn (biogas with 92% methane).

Table 1
Energy efficiency of the dryer in Ajuricaba.

Load	Unit	247	100	250	470
Total energy – E_t	kJ	4,075,928	1,647,782	4,108,238	7,730,033
Initial mass – MI	kg	14,820	6000	15,000	28,200
Final mass – MF	kg	14,198	5748	14,370	27,016
Drying efficiency – EEs	kJ/kg	6548	6539	6521	6527

both in kJ, converted using the following formula:

$$E_t = E_e \times 3600 + E_c \times 4.19 \quad (1)$$

where E_t is the total energy of the system (in kJ), E_e is the electricity consumption (kWh) and E_c is the energy consumed by fuel (kcal). The efficiency can then be calculated using the formula

$$EEs = \frac{E_t}{MI - MF} \quad (2)$$

where MI is the initial mass of the product (kg), MF is the final mass (kg) and EEs is the efficiency of drying (kJ/kg) of water evaporated. The main efficiency results for some experiments performed with the dryer can be found in [43] and are summarized in Table 1.

3.3. Prospects of use: avian, stove, water heater and others

Besides the use in the grain dryer, producers can use biogas for cooking, heating water for bathing and heating water to clean cow-milking equipment [46]. These applications bring comfort to the families of farmers, besides reducing costs and increasing income.

In rich industrialized countries, biomass represents on average about 3% of the total amount of primary energy carriers. In the emerging markets it accounts for 38%. In some particularly poor countries it reaches even more than 90% [33]. For example, Nepal, a developing country, has 145,000 biogas plants for a population of about 20 million with 9 million cows and 7 million other useful animals. It is hence the country with the highest number of biogas plants per inhabitant [39,46,55]. The number is expected to increase by another 83,500 plants, financed through the World Bank [33]. In Vietnam, 18,000 biogas plants were built by the year 2005 and another 150,000 are planned to be constructed by 2015 [38,46]. Today, in India, about 2.5 million biogas plants are running, with an average size of 3–10 m^3 of digester volume. Depending on the substrate, the plants generate 3–10 m^3 biogas per day, enough to supply an average farmer family with energy for cooking, heating, and lighting [40,42]. In China, installations of small self-made biogas plants started since the 1970s [36]. These so-called “power plants at home” were attached to private rural houses. The costs for such constructions were quite significant. About 6 million biogas plants were set up in China, promoted by the Chinese government to provide energy, for environmental protection, and to improve hygiene. The “China dome” bioreactor became a standard construction and an example for other developing countries [55]. In China, the plants were usually integrated in productive agricultural units, i.e. cooperatives. Any waste is collected and brought to a central biogas plant of 200 m^3 volume, where it is transformed into fuel. The fuel was used for cooking, to heat the living rooms, and to drive electrical generators. At the same time, the process in the biogas plant kills the germs in the feces, leaving a hygienic residue for use as fertilizer [36].

One of the prospects for immediate use of the thermal energy produced in the rural Brazil is the fact of locality in aviaries and in channeling household biogas in stoves. Local manufacturers of cookers donated household equipment so that biogas can be burned and used to heat food. For the development of equipment, the companies made some adjustments to the combustion system and to other components of the stove that produces flames regularly and continuously, thus making it safe. The quality of the flame, color and smell are completely similar to that of a conventional oven (gas butane or liquefied petroleum gas, LPG).

There are several types of biogas stoves in use across the world. An example is the Peking stove that is widely used in China and the Jackwal stove widely used in Brazil. The Patel Ge 32 and Patel Ge 8 stoves are widely used in India, and the KIE burner is used in Kenya [47]. The efficiency of using biogas is 55% in stoves, 24% in engines and 3% in lamps [48].

There are other kinds of applications too nowadays. Important examples on the general use of biogas in countries like Turkey,

Algeria, Nigeria, Ghana, Nepal, India and China can be found in [19,36–39,46–58].

3.4. Thermal energy generated parallel to power (power co-generation)

Biogas can be used in parallel to the production of electrical and thermal energy. For example, the Ajuricaba MCT allows such production and indeed the grain dryer described above uses this electric power particularly in the operation of the 5 HP electric fans. In general, the parallel production units are called “Combined Heat and Power Generation Plants” (CHP) based on obtaining electrical power by Otto cycle heat engines (four strokes) or diesel cycle [23,31,33,59].

Other forms of energy production within biogas CHPs occur from the use of Stirling engines, gas turbines, fuel cells (under high or low temperatures) or a combination of fuel cells and gas turbines [33,60–63]. Fig. 9 presents a summary of the efficiencies and ability to generate energy from some of the cited methods, thus showing that the typical efficiency of the systems used in Brazilian agroenergy condos (Otto/diesel engines) has values around 30–40%. Moreover, as is going to be discussed in Section 5, even vehicles can be moved by thermal energy from the biogas (e.g. by temperature differences in a simple Stirling engine) or by means of electrical energy (from fuel cells) [60].

4. Utilization of electrical energy from biogas

4.1. General use of biogas for electricity generation

In electricity generation, motogenerators of synchronous or asynchronous types can be used. In most cases synchronous generators are used and only in the case where electricity is generated with a power below 100 kW it is customary to use asynchronous generators. Otto cycle thermal engines or diesel is commonly coupled to the generator.

One of the possible goals is to use generators as suppliers of electrical current to the grid. In this case, the generation system must be coupled with an electrical transformer with a four quadrants voltage meter as standard. The connection of a synchronous generator is properly made when the following conditions are met: the variation of voltage delivered to the network should not exceed 10% of the nominal voltage of the network, the frequency of the signal generated should not exceed a variation of 0.5 Hz, and phase angle does not have a variation greater than 10 degrees. To this purpose, it is expected that the programmable controller (PLC) that connects the signal from the equipment to the power grid complies with the conditions reported above.

Here we will describe preferably the generation of electricity from biogas using Otto cycle engines or diesel, although other forms of generation, especially in large plants, can also be used in the production of steam from burning biogas to generate electricity from organic Rankine cycle turbines, Cheng cycle, etc. [33]. In the specific case of the Otto cycle or diesel, Fig. 10 shows the basic system of generation containing the combustion engine, the electric generator, the instruments of control, compressor and other parts. Table 2 shows some characteristics of generators based on Otto cycle (four strokes), pure diesel cycle, and diesel cycle with spark ignition (e.g., this last one is the case for the Ajuricaba MCT).

4.2. Criteria for generation and distribution of energy produced in Brazil

The power generation in distributed mode is currently the most common form and has the highest growth in the world, having already exceeded in 1990 the total installed capacity in isolated systems [64]. In Brazil, the generation, transmission and distribution of electricity are utilities regulated by a federal agency, the National Agency for Electric Energy – ANEEL, whose

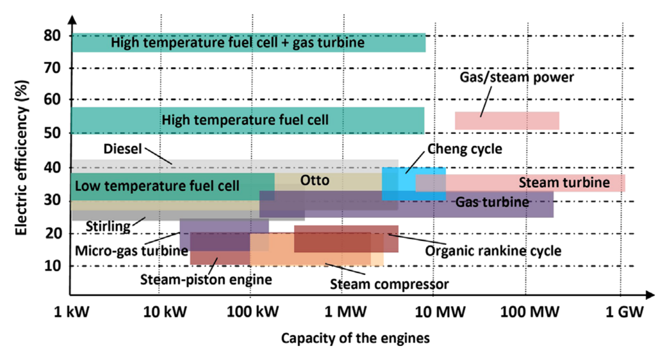

Fig. 9. Thermal machines used in power generation and their respective efficiencies capacities [33].

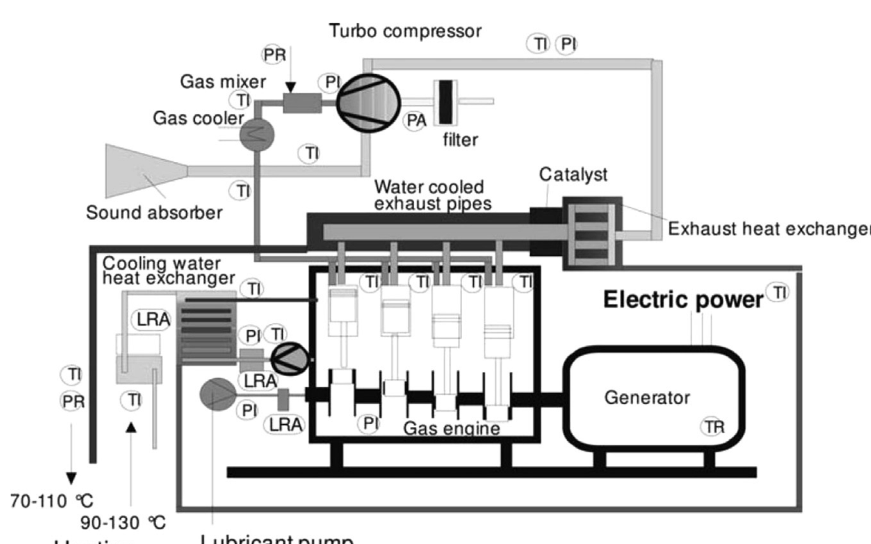

Fig. 10. Component parts of a system for generating electricity (motogenerator). Both in Ajuricaba and in Colombari there are diesel cycle engines, fitted with candles to simulate a cycle Otto (diesel ignition).

Table 2
Characteristic values for Otto and Diesel biogas engines motogenerators.

Feature	Four-stroke engine	Gas–diesel engine	Ignition oil diesel engine
Range of capacity (kW_{el})	<100	>150	30–1000
Spec. investment-costs (US$/$kW_{el}$)	1200	1300	1300
Spec. maintenance-costs (US$/$kWh_{el}$)	High	Low	High
Electrical efficiency	30–40%	35–40%	32–40%
Decrease of efficiency at partial load; given value for 50% load	High 84%	Low 84%	Low 84%
Cooling water temperature	110 °C	110 °C	110 °C
Revolutions per minute	1500 U/min	1500 U/min	1500 U/min
Pressure ratio	10:1	20:1	20:1
Controllability of the power/heat ration	Not possible	Not possible	Not possible
Weight	Medium	Medium	Medium
Lifetime	Medium	Medium	Long
Noises	Medium	Loud	Loud
Emissions NO_x	High	High	Carbon black 600–700 mg/N m^3
Alternative fuel in case of shortage of biogas	Liquid gas (gasoline)	Liquid gas	Petroleum (vegetable oil)
Minimum heating value	Medium	Medium	High (10–30% ignition oil)

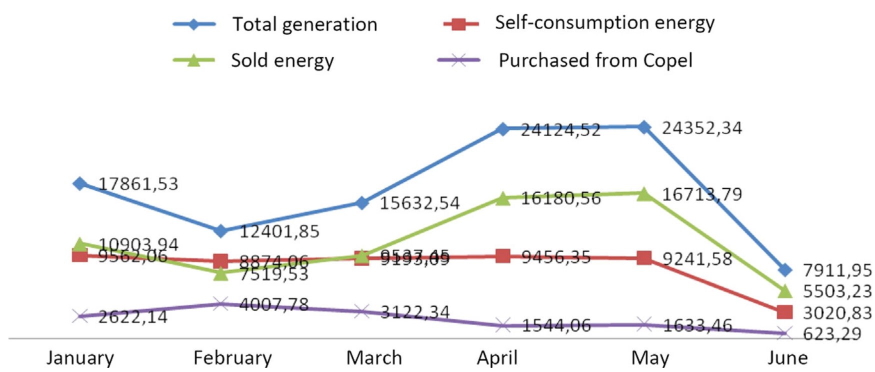

Fig. 11. Quantitative values (in kWh) obtained in the first half of 2012 in power generation, energy exported to Copel (sold), energy consumed and energy purchased from Copel in Granja Colombari from the electricity generated in the production of biogas.

jurisdiction is based on art. 21, XII, of the Constitution of 1988 and the Federal Law of 9427 1996. ANEEL is therefore relevant not only to monitor but also to regulate, that is, to detail how these utilities will be provided. And, in the exercise of its regulatory power it released Resolution 167/2005, which was the first attempt to organize the distributed generation [65] but may not have provided the regulatory certainty necessary to broaden the large-scale production of small household generators.

Until recently in Brazil, for networking, the maximum allowed power is up to 300 kVA, with the metering billing system (four quadrants). For self-supply, there are no power limits and this is the most advantageous condition concerning economic return for the energy generated in familiar agriculture. In Brazil, the sale of surplus electricity can be conducted through contracts with the distribution utilities by public calls, governed by the rules of ANEEL. In 2009 there were significant changes in this regulation. Normative Resolutions 390/2009 and 395/2009 set by ANEEL changed the criteria Procedures for Distribution in the Electricity Sector (PRODIST), allowing the electricity produced by generators smaller than 1 MW to be connected to the grid [59]. This came from a public hearing to gather public suggestions on distributed energy and their regulation in Brazil, which resulted in the Technical Note N. 4/2011 [66]. This Technical Note subsidized the discussion that followed, yielding the new regulatory standard: Resolution 482/2012 [67], which can be called a new regulatory framework for distributed microgeneration and minigeneration in Brazil. Based on this standard, the domestic consumers and small farmers, connected to the distribution network, can also generate their own power by alternative power sources.

All the advances that have been made to consolidate a Brazilian low carbon agriculture based on the use of biogas were only possible thanks to the Normatives described above, establishing the conditions for micro and small generators to be connected to the distribution network. By resolution, any electricity distributor is authorized to make public calls to buy electricity produced by these small generators. The distributed generation system enables the decentralization of power generation, promoting power autonomy for Brazilian communities, municipalities and regions.

The operation patterns in Western Paraná were obtained from tests promoted by Itaipu in partnership with Companhia Paranaense de Energia (Copel) and Sanitation Company of Paraná (Sanepar) in six demonstration units, in a process that took 5 years. Two examples are provided regarding such units: (I) midsize property with individual use in Colombari farm (São Miguel do Iguaçu, Paraná, Brazil); and (II) small collective of family farms in Condo Ajuricaba. In particular, the virtue of Ajuricaba lies in the fact that 33 properties unite to distribute biogas from a pipeline that will serve as a vector for the feasibility of generating electricity from microplants.

The hiring of energy in this system represents a paradigm shift in the Brazilian electricity sector, which has always been planned based on large enterprises, thereby configuring the inauguration of a phase in which it demonstrates the technical feasibility, economic and environmental generation below 1 MW. The sum of many small producers in condominiums is very interesting from the point of view of energy, especially nowadays, in that climate change imposes the need to develop increasingly optimized renewable energy.

Nevertheless there are some limits, since that in the described Normatives the consumer cannot be compensated monetarily, unlike what happened in other countries like Spain and Germany by means of feed-in tariff [68], which causes distributors to pay more for the consumer by the energy generated from alternative forms of the same energy received by the consumer pays the grid, generated mainly (in the case of Europe) from fossil fuels [69]. For all details regarding microgeneration in Paraná, Brazil, see [70,71].

4.3. Example 2: power generation in Colombari farm, Paraná, Brazil

The Colombari farm, located in the municipality of São Miguel do Iguaçu, also in western Paraná, Brazil, has a pilot production of electricity from biogas. This pilot, technically managed by Itaipu, configured as reference prior to the generation of electricity in Ajuricaba. The farm, belonging to a mid-sized producer, has a roster of 3000 hogs, and from 2009, with the commissioning company's local electricity distributor (Copel), went on to sell the surplus produced in power generation (in the form of power credits).

Currently, the Paraná dealership conducts on-site testing and has met with the National Electric Energy Agency (ANEEL) to establish parameters for the definitive implementation of distributed energy generation from biogas in Brazil.

The employed motogenerator has the capacity to generate 30 kW of electrical power. The generator works between 07:00 am and 19:00, totaling 12 h of generation per day not working on Sundays. Therefore, nominally, it is expected that the actual power generated daily is for the above data on average of 360 kWh, which would provide a monthly average generation (including Sundays) of 9360 kWh. In everyday terms, 60% of the energy produced, i.e. 216 kWh, is consumed on the farm, and the remaining 40% (144 kWh) is sold to Copel. A quantitative statement of generation can be seen in Fig. 11 and gains on the sale of credits in Real-equivalents of Brazil can be seen in Table 3.

4.4. Generation of electricity in Ajuricaba and socioeconomic differentials

Harnessing the power in the MCT Ajuricaba is accomplished using a 100 kVA group motogenerator, with connection for distributed generation (Fig. 12). The actual structure installed in the MCT allows four motogenerators. The engine system is a Mercedes Diesel fitted with plugs and regulator/pressure reducer to facilitate combustion of biogas. The biogas pipeline entering the system comes purified from the biogas processing unit of the MCT containing methane at most 90% and very low concentrations of H_2S, which could be detrimental to the proper functioning of the combustion chamber of the engine.

One of the technologies developed in the rigging of the MCT electric generation of power is the control panel and synchronization of electrical energy generated by the distribution network. Such a system of Monitoring, Control and Protection is an inexpensive tool that ensures that the energy generated from distributed generation can be marketed without restriction.

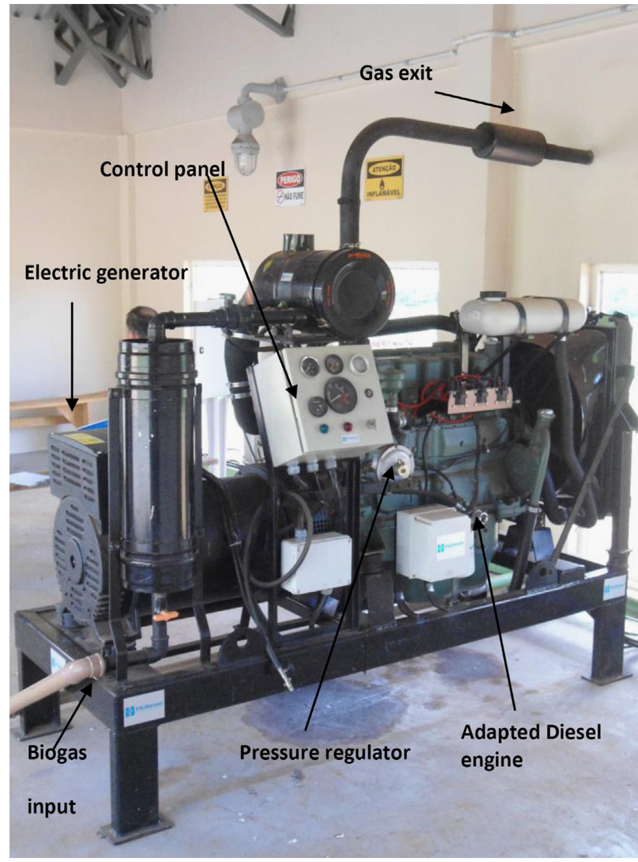

Fig. 12. Motogenerator present in the CAAF for generating electricity from the combustion of biogas. The electric generator has a capacity of 100 kVA.

Table 3
Estimated incomes in 2012 for Granja Colombari (in Brazilian Reals; R$ 1.00–US $ 0.50).

Month	Copel	Avoided cost	Debts Copel	Balance
January	R$ 1545.96	R$ 1346.23	(R$ 508.65)	R$ 2383.54
February	R$ 1066.12	R$ 943.97	(R$ 777.44)	R$ 1232.65
March	R$ 1352.22	R$ 1177.62	(R$ 605.68)	R$ 1924.16
April	R$ 2294.08	R$ 1534.85	(R$ 299.52)	R$ 3529.41
May	R$ 2369.68	R$ 1475.85	(R$ 316.86)	R$ 3528.67
June	R$ 780.25	R$ 465.08	(R$ 120.91)	R$ 1124.42
Total	R$ 9408.31	R$ 6943.60	(R$ 2629.07)	R$ 13,722.84

There are two possible purposes for the electricity generated by the MCT in Ajuricaba. The first and better one is the use of energy to self-supply the property. Another purpose is to sell the surplus energy to a distribution network (i.e., Copel). Currently there is a public call contract to sell surplus power to the distributor in the form of power credits. Other experiments or biogas pilot power plants in Brazil are also presented, e.g., in [3,19,22,23,59].

5. Biogas energy and perspective for vehicular use in Brazil

One of the greatest economic potential applications that biogas can offer is its use as an automotive fuel. This experience has already been carried out mainly in European Union countries, with promising developments in some Asian countries [32,34,35,72–78]. In Brazil particularly, the improvement of this technology is still slow, although the potential use is outstanding.

For safe use of biogas in automotive engines chemical purification of the fuel is necessary, making it possible to obtain biomethane (methane over 90%) since the presence of gases such as H_2S can impair the engine's constituent parts in its combustion chamber, resulting from corrosive reactions.

In this section the likely development of vehicle fuel pumps at Condo Ajuricaba will be addressed. Firstly, however, it is reported on how biomethane from biogas can be used in vehicles.

5.1. Vehicular technology for the use of biogas

Biogas is similar to natural gas with a high calorific value and it can replace many applications. The advantage of biogas in relation to

natural gas is the fact that it is renewable and produced in all places where there is biomass. The disadvantage is its lower calorific value and the presence of H_2S and humidity [23]. The spark ignition engines, powered by gasoline or diesel engines converted to Otto cycle, can be easily converted to gas engines. The same techniques for converting gasoline engine to natural gas are used for biogas. Biogas has a calorific value of approximately half the natural gas. Such property indicates that the engine carburetion system must be sized in a manner that the flow of biogas should be two times higher than that for the natural gas to maintain a fix power [79,80]. The main modification of a gasoline engine for biogas is installing a gas–air mixer in place of the carburetor. The motor control is done by controlling the air/fuel mixture by the variation of the valve pressure, similar to the butterfly valves present in petrol engines. Other modifications include changing the compression ratio and introducing spark advance [81–83].

In light vehicles (cars), it is possible to adapt the use of compressed natural gas (CNG) or biomethane engines operating on the Otto cycle (spark ignition) with air–fuel mixture with stoichiometry that offers better performance, equipping the engine with a catalytic converter with a three-way pressure regulator. In most cases these vehicles have a function “bi-fuel”, which maintains a gasoline tank system (or ethanol) next to the gas supply system. This allows the vehicle to be used according to the circumstances, namely using either petrol (ethanol) or biomethane/CNG. However, in some cases, the vehicle is designed to run only on natural gas or biomethane and it is optimized for operation in single fuel. Fig. 13 shows an example of bi-fuel Swedish vehicle (Volvo S80) that has to adapt to the use of biomethane working with the gasoline mode [30].

For heavier vehicles, such as tractors, trucks or buses, the system usage is a little different for both spark ignition engines as the compression ignition. The engines for such cases are based on the diesel cycle, although they may be adapted for spark ignition instead of compression ignition, being designed to operate solely on gas. One of the advantages of using biogas in such engines is that the adapted ones become 50% quieter than their diesel equivalents [83,84].

The storage of fuel in the vehicle, in both cases above, can be made into compartments where fuel is compressed or liquefied. A compressed form is the most commonly used, where the biogas is stored at high pressure (typically 200 bar) in specially designed tanks [85]. An operational problem is that the stored energy for a given volume of biogas is lower than for the same volume of liquid fuel (diesel, for example). Thus, the performance of the vehicle tends to be lower for biogas. For cases where large torques are required, as in heavier vehicles, liquefied biogas becomes more advantageous [83]. The liquefaction process is achieved by specific further compression, refrigeration and storage in specific tanks.

5.2. Quality of biogas for automotive use

The key standards for quality certification of biogas for automotive use are those specified by Sweden (SS 15 54 38) and proposed by Chinese Official Standards [86]. According to the International Organization for Standardization (ISO), 12 countries participate in the creation of a broader standardization for biogas [17], called the Technical Committee for the Biogas (Biogas TC 255). This standardization began in 2010 and 18 countries in the world are presently observing it. Brazil is not officially observing the norms. In particular, the standardization reference in the European Union, the Swedish SS 15 54 38 [86], is currently restricted to the use of biogas in Otto cycle engine fast vehicles.

The principle for understanding the required quality of biogas comes from the Wobbe number

$$W = \frac{H}{\sqrt{d}} \tag{3}$$

expressing the relationship between the calorific value H of the gas and the relative density d between gas and air (d is gas density divided by air density). The relative density d is therefore a dimensionless quantity. The calorific value H expresses energy that is obtained by burning a standard cubic meter of gas and is given in kWh/m^3 or MJ/m^3. For biogas with 100% methane, the value of H varies between 9.97 and 11.06 kWh/m^3 and with 97% methane H varies between 9.67 and 10.73 and 60% methane H ranges between 5.98 and 6.64 kWh/m^3 [76,87]. For automotive use, the ruling Swedish SS 15 54 38, reference in the European Union, uses biogas with Wobbe number that should range between W=43.9 and W=47.3 MJ/m^3, with percentage of methane 97 ± 2% [86].

In addition, the other main influencing factors in using biogas as a combustible gas are gas/air mixing rate, flame speed, ignition temperature and gas pressure. Compared to liquefied petroleum gas, biogas needs less air per cubic meter for combustion. This means that for the same amount of air more gas is required. Therefore, gas jets are larger in diameter when using biogas. About

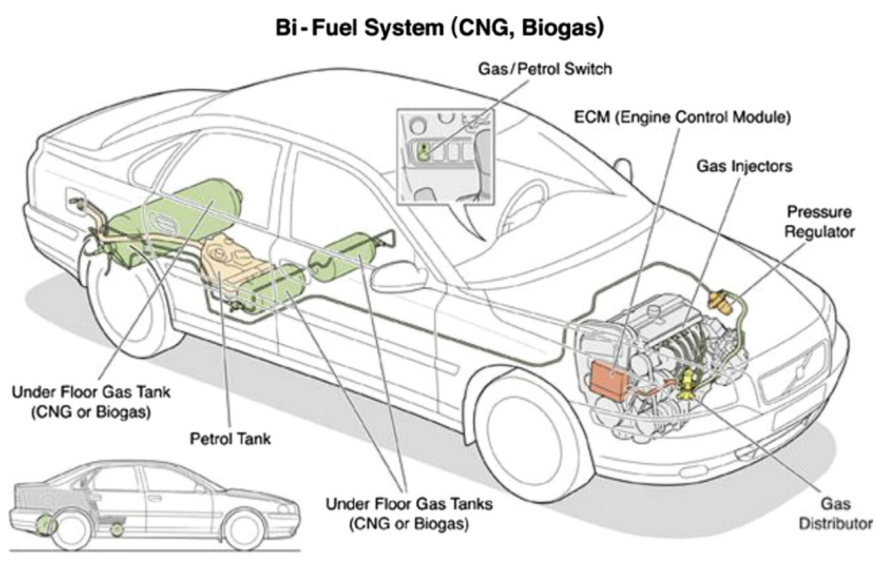

Fig. 13. Example model of bi-fuel Volvo S80 (gas/biomethane or gasoline/natural gas) [80]. In the Fig., which indicates the use of biogas, read biomethane (purified biogas).

5.7 l of air is required for total combustion of 1 l of biogas, while for butane it is 30.9 l and for propane 23.8 l [48,87].

5.3. Prospects of automotive use of biogas as fuel in Brazilian condominiums of agroenergy

As a future perspective, the idea on the route of biogas is its use in a processed and filtered way to obtain biomethane capable of fueling pumps for use in vehicles of the agroenergy condos such as tractors and rural machinery. Another idea is to reform the biogas with low methane content itself to obtain hydrogen that can feed fuel cells.

The MCT unit in CAAF has a Treatment Unit Biogas – UTB. This UTB has the purpose of filtering crude biogas properties routed from 33 composing the condominium, reducing H_2S concentration, reducing the concentration of CO_2 and thus increasing the concentration of methane (CH_4). It may be noted that despite the high concentration of obtaining biomethane (about ~92%), the CAAF not yet reached the levels normalized by the Swedish SS 15 54 38. However, at the experimental level, since the calorific value is high (producing a Wobbe number of the next appropriate), one can create a small fuel station for using biomethane produced in machines adapted for its use. Concomitantly, we expect to obtain improved levels in future biomethane to approach international regulatory requirements. Once such levels are reached, one can construct pumps in the automotive adapted condominium itself or within the MCT to supply biogas purified for use in vehicles of farmers (since the machine is adapted for the use of biogas).

6. The use of biogas in Brazil energetic matrix: advantages for small farmers

The role of technology developed in MCT Ajuricaba, as shown in the previous sections, emphasizes applications of renewable energy in Distributed Generation, which is approved by ANEEL – Brazilian Electricity Regulatory Agency to supply biogas. The feasibility of the proposed system or, briefly, the co-generation with biogas, can be seen not only by the production of low-cost energy and energy independence, but especially by demonstrating that it is a sustainable solution.

Besides Ajuricaba, in western Paraná five Demonstration Platform units are installed whose main purpose is replicating this success regionally and in national and international scales. The Platform also promotes energy efficiency in regional Paraná Basin 3, sustainable mobility and sustainable development from the use of solar, wind, biomass and hydro.

It was previously shown that transforming the environmental problems generated by economic opportunity in agricultural production is a major goal of Agroenergy Condominium Projects (CAAF). Ajuricaba, for example, is expected to generate an extra income to 33 small farms involved in the experiment, where approximately 48 m^3 per day of waste produced in these properties will be converted into electrical energy, thermal and also automotive, whereas purified biogas behaves like CNG. The energy from biogas, the most affordable and best value in the Brazilian countryside, thus becomes an item of the energetic matrix capable of supporting development in the countryside and offers small producers a stable source of income in a situation marked by volatile prices and the consequent difficulty in planning their economic activity. Important features related to hydrogen reformation of biogas are also in the condominiums agenda [60]. A schematization of a typical Brazilian CAAF (e.g. Ajuricaba) as generator of clean energy can be seen in Fig. 14.

7. Concluding remarks

The Brazilian Agroenergy Condo facilities thus become promoters of sustainable rural production for small farmers, showing the feasibility of transmuting the environmental liabilities of the Brazilian agricultural sector into electricity and fertilizer. The product of this activity, after paying the investments made to structure and power generation, also generates income for the condominium farmer family.

This work explored the technological issues of the simultaneous generation of thermal and electrical energy in a micro co-generation

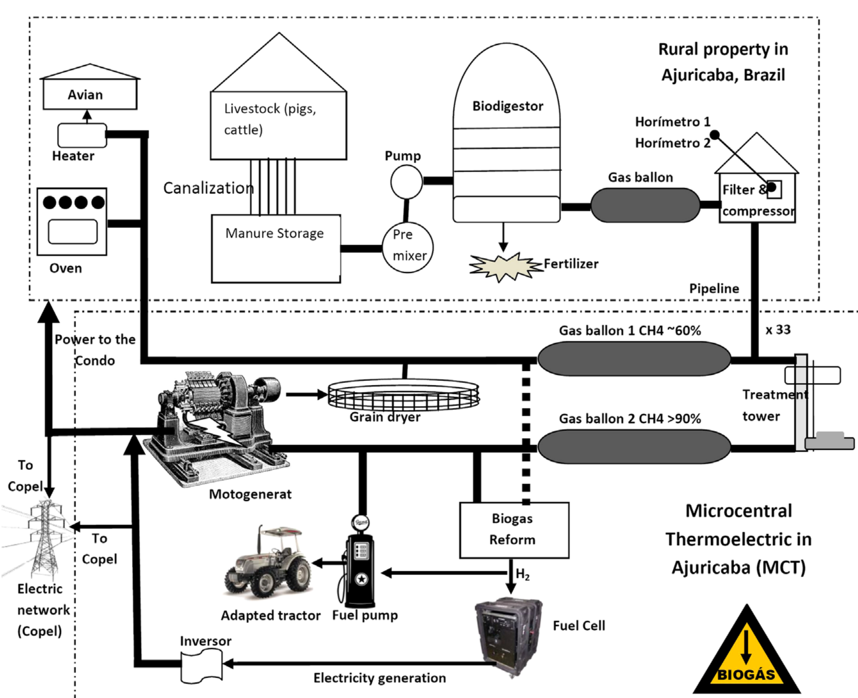

Fig. 14. Scheme of production of biogas in rural property and its use in generation of thermal energy (reality), electrical (reality) and automotive (perspective) in Ajuricaba, besides obtaining hydrogen from the refining process.

unit located in typical Brazilian agroenergy condominiums, from the use of biogas as a renewable fuel produced from waste by the process of anaerobic digestion. The article contextualized two examples of rural use of biogas energy in Brazil, the Ajuricaba Condo and the Colombari Farm, and their main physical and geographical aspects, introducing an overview on biogas energy production in these locations. The work also explored how biogas can be used for self-generation, used in the production of surplus electric power and in the development of new technologies such as the control panel to synchronize the electricity generated with that from the distribution network, and the prospects for implementation of a pilot system for use of biogas in vehicles. From the material presented, one can conclude that the feasibility of the proposed system or, briefly, the co-generation with biogas in familiar agriculture rural properties can be observed not only by the production of low-cost energy and energy independence, but especially by demonstrating the environmental viability in generation.

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